Simulation of Scrape-Off Layer Magnetic Field in W7-X

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Introduction

Coil missallignment has been confirmed as the main source of error fields in W7-X.

- The effect on limiter connection lengths is examined.
- Predictions of divertor asymmetries are made.
- Validation of fieldline diffusion is presented.

Methods

In order to understand scrape-off layer physics, we trace fieldlines with the FIELDLINES code.

- CAD, measured, and FEM coil models[1] are used.
- Limiter connection lengths are examined.
- Fieldline diffusion implemented to model divertor heat loads.

Fieldline Model

The equation of motion of a fieldline is $\frac{d\vec{R}}{ds} = \frac{\vec{B}}{|\vec{B}|}$. In cylindrical coordinates, applying $\frac{d\Phi}{ds} = \frac{B_\Phi}{R|\vec{B}|}$ yields the equations of motion $\frac{dR}{d\Phi} = \frac{RB_R}{B_\Phi}$, $\frac{dZ}{d\Phi} = \frac{RB_Z}{B_\Phi}$ for a toroidal field. These equations are integrated over Φ to trace fieldlines.

Diffusion is modelled by adding a perpendicular displacement $\vec{\delta} \cdot \vec{B} = 0$ to the equation of motion $\frac{d\vec{R}}{ds} = \frac{\vec{B}}{|\vec{B}|} + \vec{\delta}$, which results in the equations:

$$\frac{dR}{d\Phi} = \frac{RB_R + |\vec{B}|\delta_R}{B_\Phi + R|\vec{B}|\delta_\Phi}, \quad \frac{dZ}{d\Phi} = \frac{RB_Z + |\vec{B}|\delta_Z}{B_\Phi + R|\vec{B}|\delta_\Phi}$$

By assuming a small field pitch, $\delta_\Phi << 1$ and $B_\Phi \sim |\vec{B}|$, we can approximate:

$$\frac{dR}{d\Phi} = \frac{RB_R}{B_\Phi} + \frac{|\vec{B}|}{B_\Phi}\delta_R, \quad \frac{dZ}{d\Phi} = \frac{RB_Z}{B_\Phi} + \frac{|\vec{B}|}{B_\Phi}\delta_Z$$

This gives a displacement $\frac{|\vec{B}|}{B_\Phi}\vec{\delta}$ in the RZ-plane which we can apply in regular intervals of Φ. For 2D Brownian motion, the standard deviation of displacement over a single timestep with diffusion coefficient D is

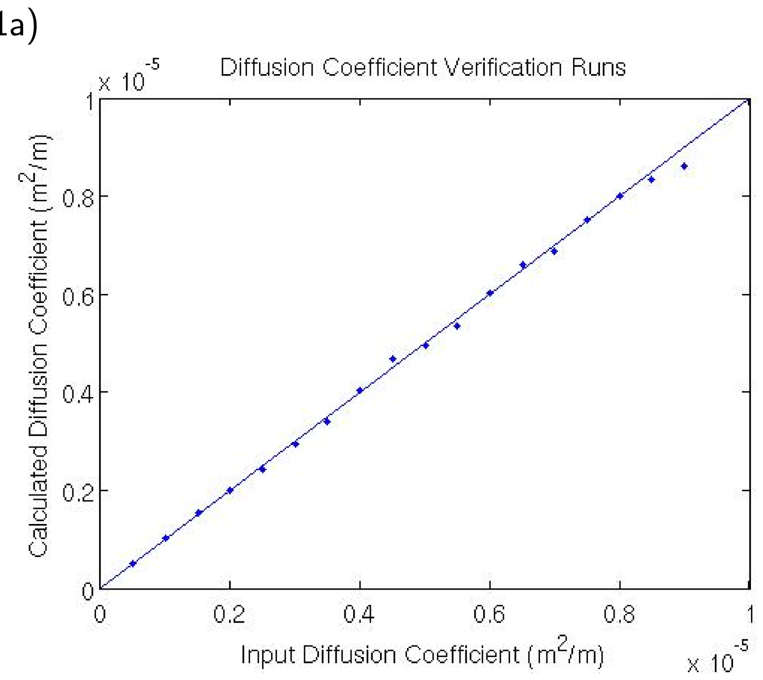
$$k = \sqrt{2Dds} = \sqrt{2DR|\vec{B}|d\Phi/B_\Phi}$$

Therefore at each increment of Φ we apply a displacement:

$$\frac{|\vec{B}|}{B_\Phi}\delta_R = \frac{|\vec{B}|}{B_\Phi} n_R \sqrt{2DR|\vec{B}|d\Phi/B_\Phi}, \quad \frac{|\vec{B}|}{B_\Phi}\delta_Z = \frac{|\vec{B}|}{B_\Phi} n_Z \sqrt{2DR|\vec{B}|d\Phi/B_\Phi}$$

where n_R and n_Z are normally distributed random values with $\sigma = 1$

1a)



1b)

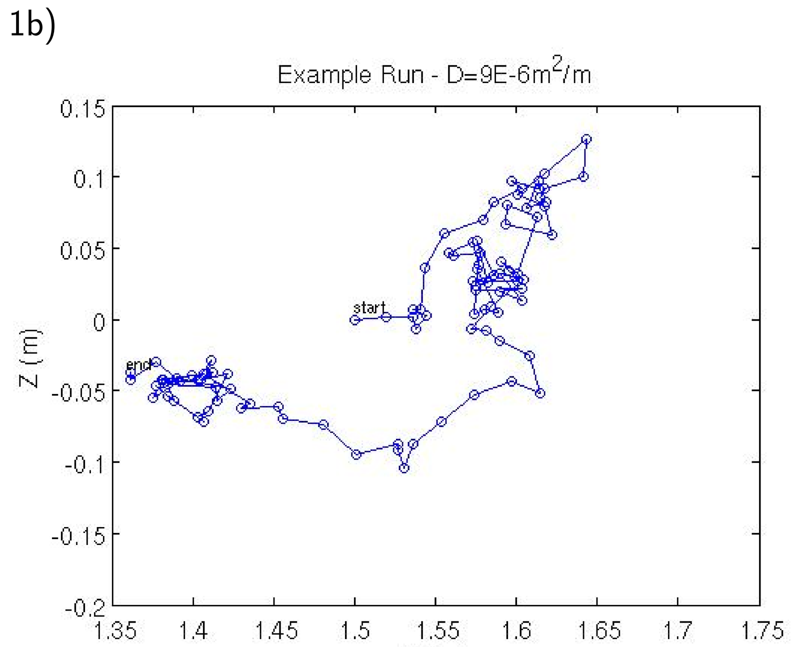


Figure 1 - Diffusion Model Benchmarking

The diffusion model was benchmarked in a purely toroidal field, tracing from a start point at $R = 1.5m$ with diffusion coefficient (D) varied. 4096 runs tracing 100 orbits at each value of D.

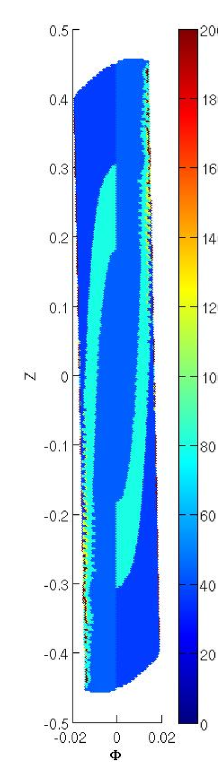
a) Diffusion coefficient verified by calculating $D_{eff} = MSD/(4 * L)$.
- MSD is mean squared displacement after 100 orbits, and $L = 100 * 2 * pi * 1.5m$ is estimated path length.
- $D_{eff} = D_{in}$ line added to plot for reference.

b) An example run illustrating random walk. Points taken at $\Phi = 0$ after each orbit.

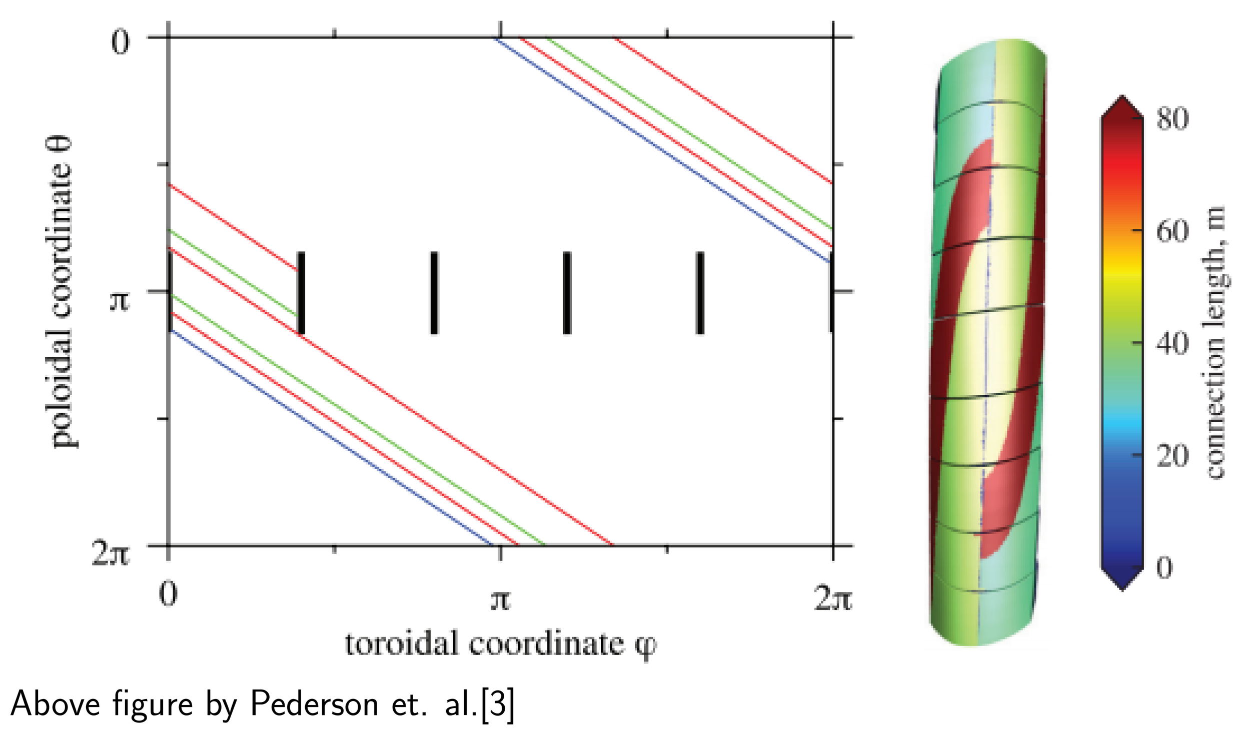
Limiter Connection Length Calculation

- Tracing confirms previous models of limiter connection length distribution[3].
- Error field induced asymmetry in limiter connection lengths resembles experimental results.
  - Features walk off limiter edge as observed in OP 1.1.

2a)

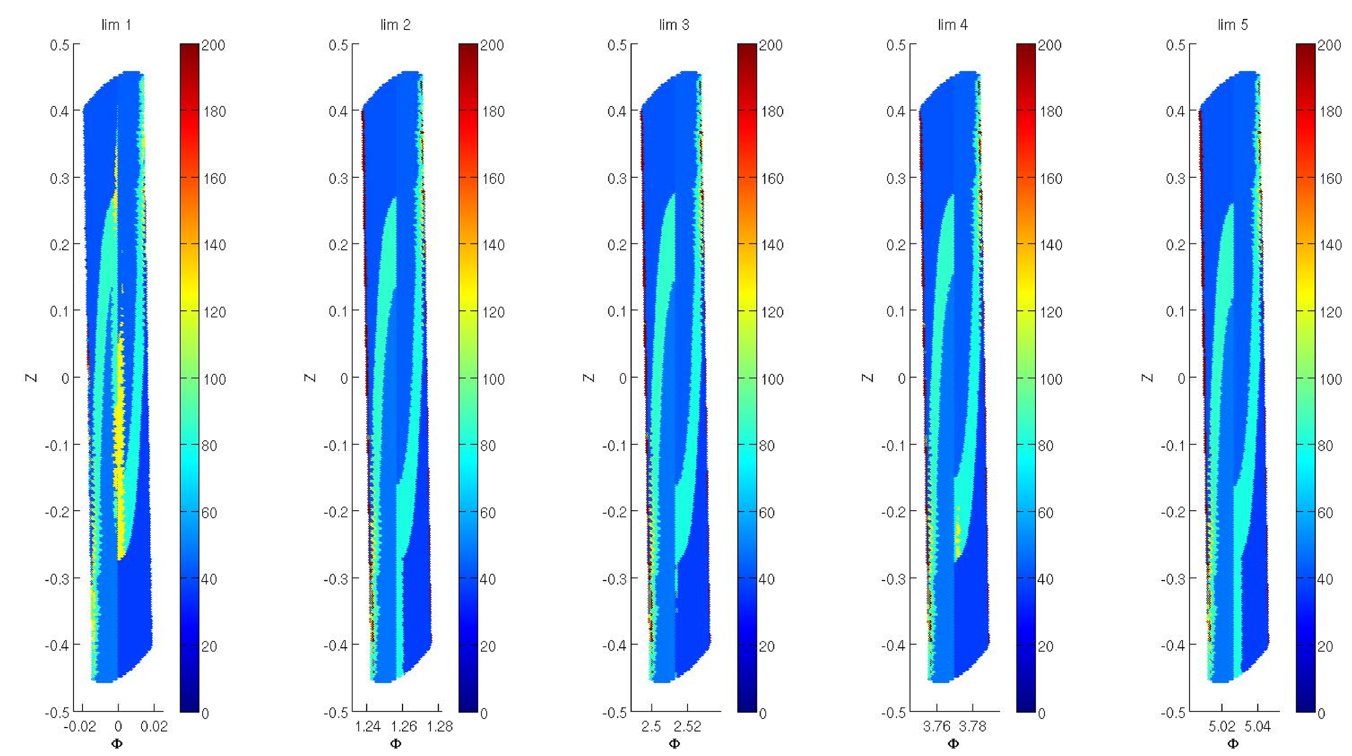


2b)



Above figure by Pederson et. al.[3]

2c)



2d)

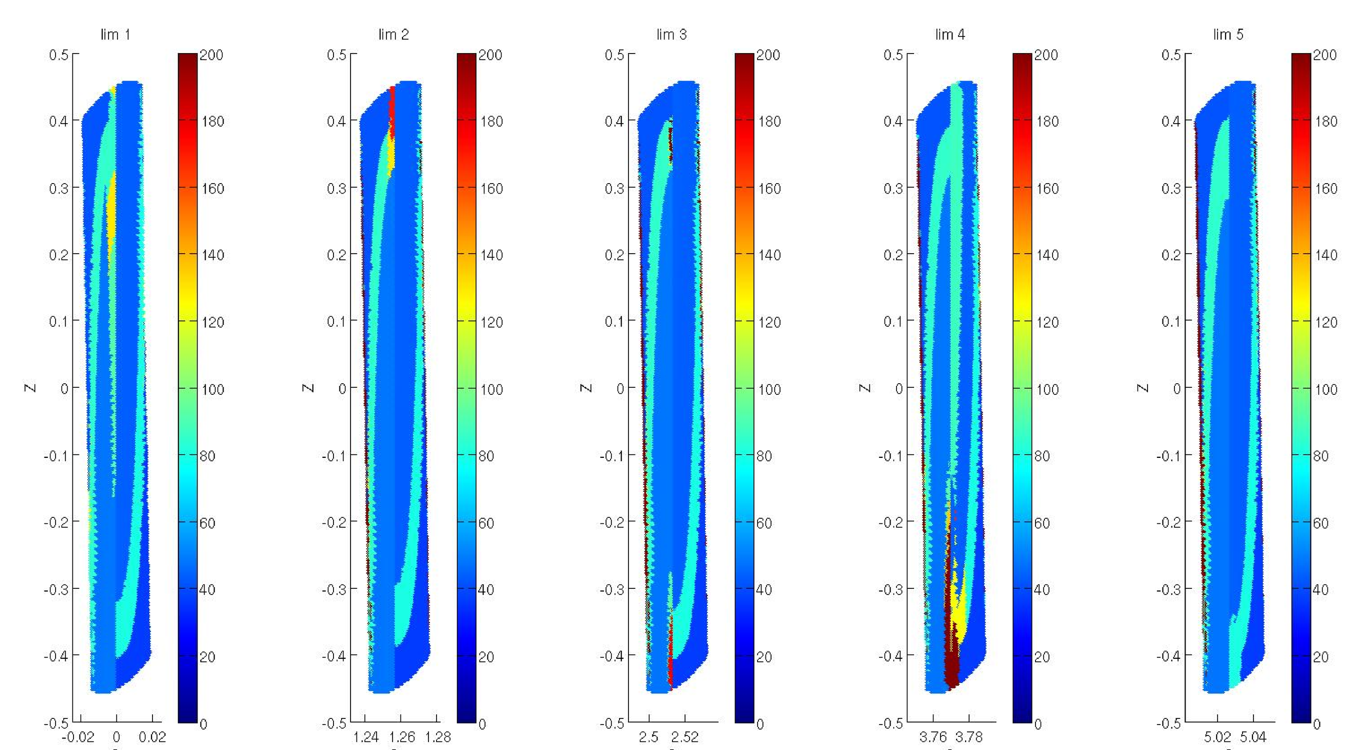


Figure 2 - Limiter Connection Lengths

All lengths in meters. All angles in radians.

a) Traced using ideal CAD coil positions, demonstrating stellarator symmetry.

b) Plots by Pederson et. al.[3] confirming results for ideal case and illustrating connection paths.

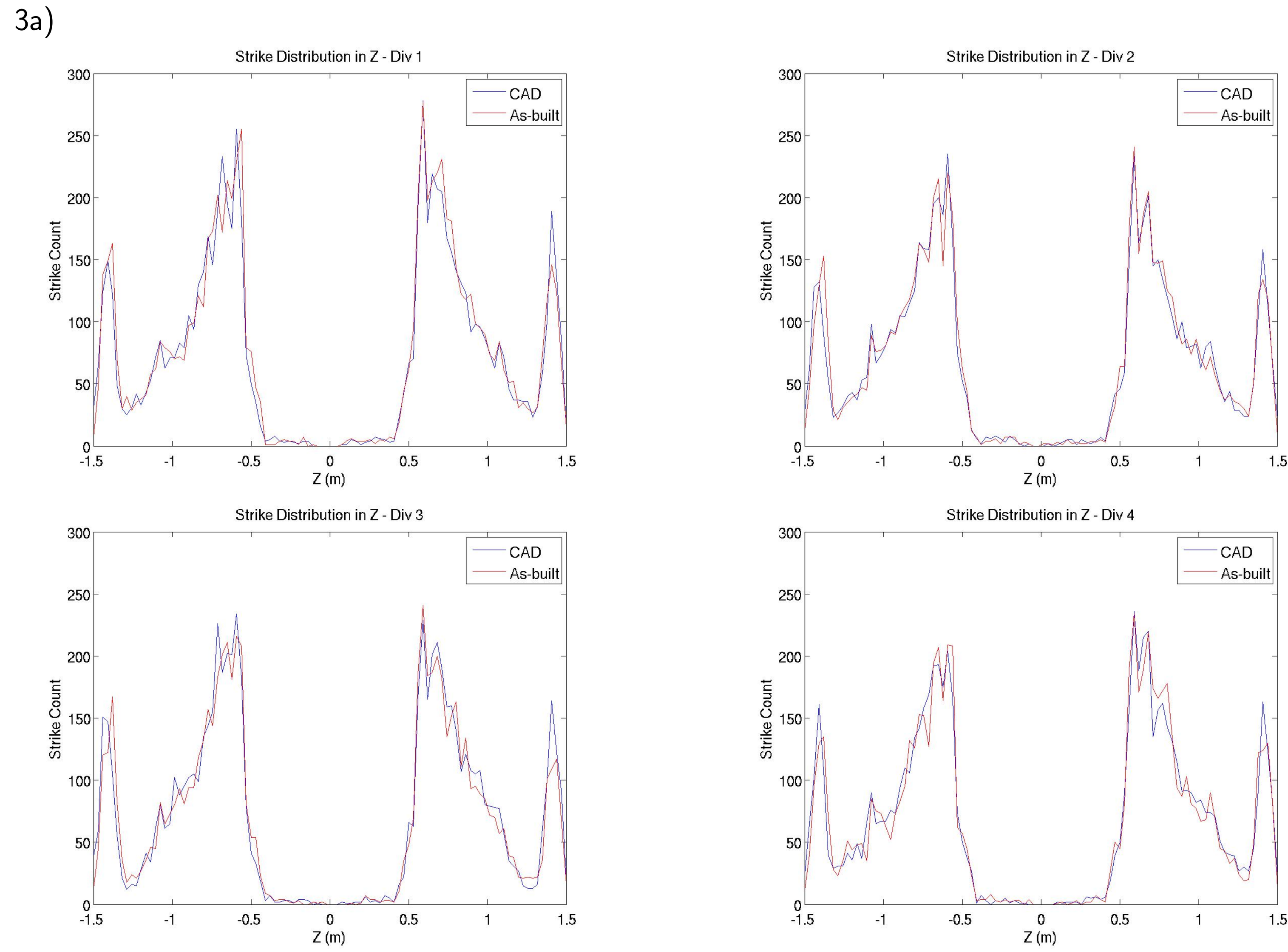
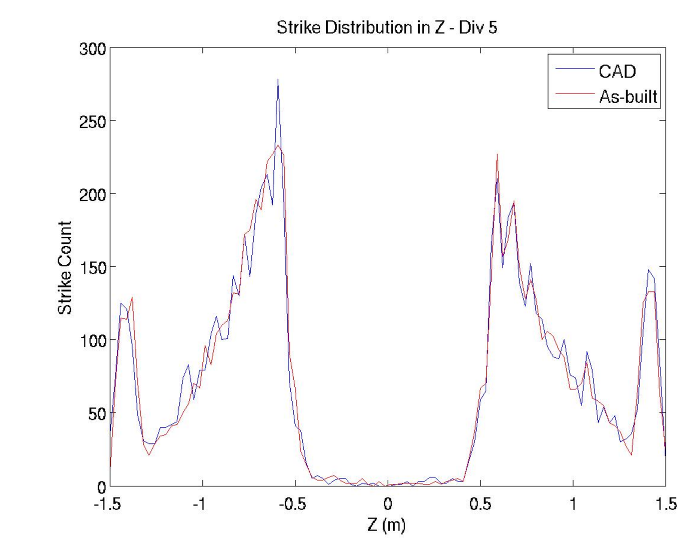
c) Traced using coils adjusted for measured deviation in construction[1], showing broken symmetry.

d) Traced using coils adjusted for deviation in construction and deformation under load calculated by FEM[1].

Diffusion Modelling of Divertor Heat Flux

- Initial results do not indicate significant load asymmetry.
- Diffusing fieldlines traced from closed surface near edge with $D = 5x10^{-4}m^2/m$.
- Further modelling required to refine predictions.

3a)

3b)

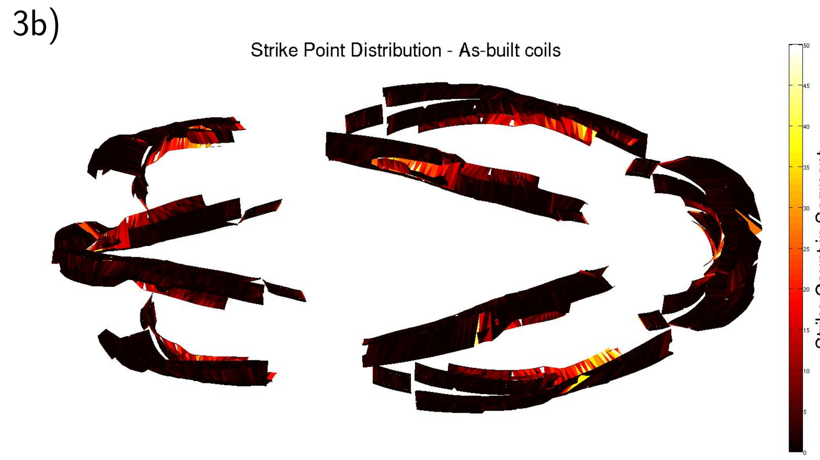


Figure 3 - Divertor Strike Point Dsitribution

a) Histograms of strike point distribution in Z (100 bins) for each divertor section. Little difference can be seen between the ideal CAD coils and coils adjusted for deviation in construction. The plots demonstrate the expected symmetry in Φ and Z.

b) A 3D model of the divertor system showing strike point distribution for the as-built coils.

References

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[2] S. A. Lazerson, M. Otte, S. Bozhenkov, C. Biedermann, T. S. Pedersen, and the W7-X Team. First measurements of error fields on w7-x using flux surface mapping. *Nuclear Fusion*, 56(10):106005, 2016.

[3] T. S. Pedersen, T. Andreeva, H.-S. Bosch, S. Bozhenkov, F. Effenberg, M. Endler, Y. Feng, D. Gates, J. Geiger, D. Hartmann, H. Hölbe, M. Jakubowski, R. König, H. Laqua, S. Lazerson, M. Otte, M. Preynas, O. Schmitz, T. Stange, Y. Turkin, and the W7-X Team. Plans for the first plasma operation of wendelstein 7-x. *Nuclear Fusion*, 55(12):126001, 2015.

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